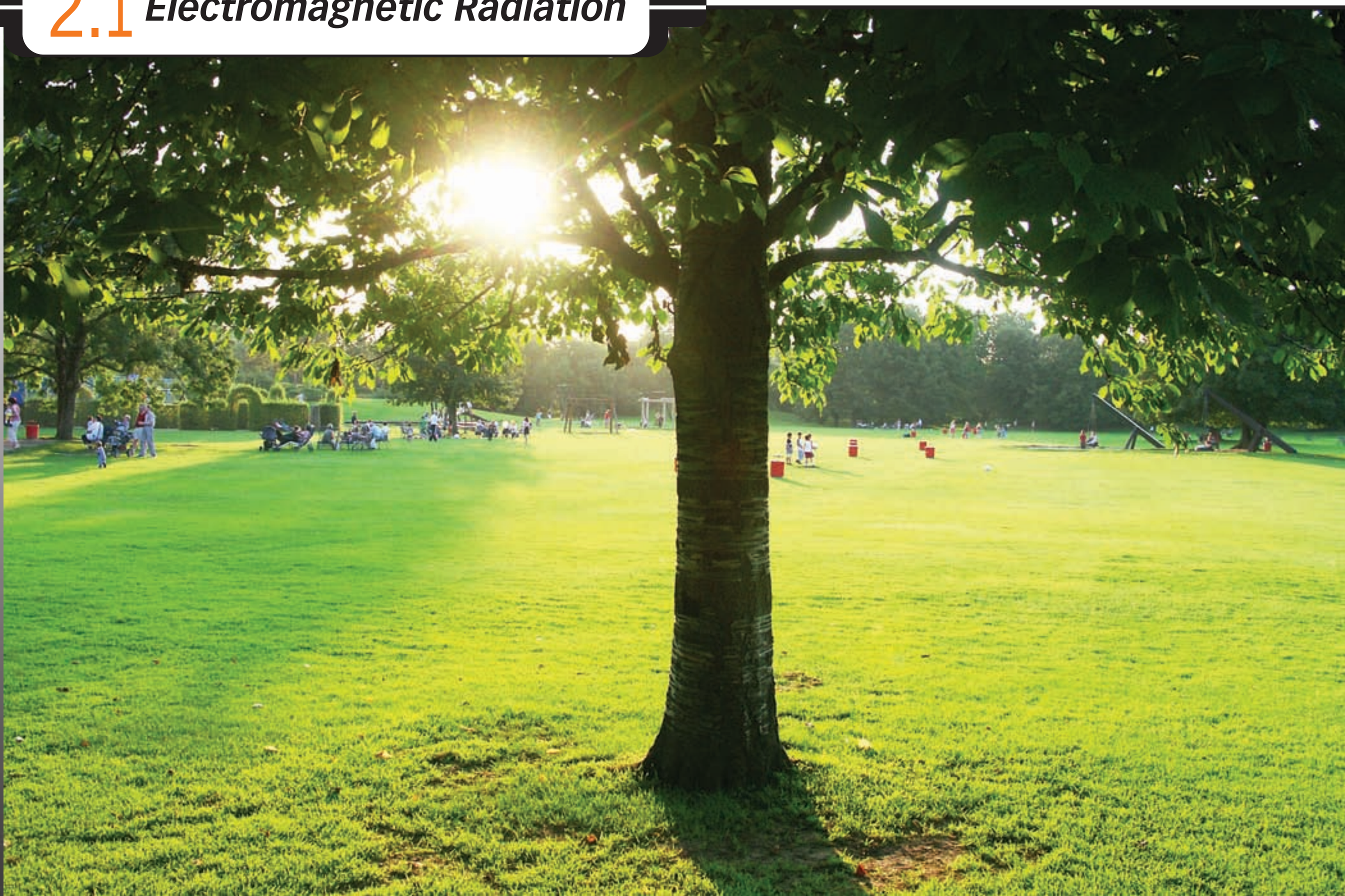
2.1 Electromagnetic Radiation



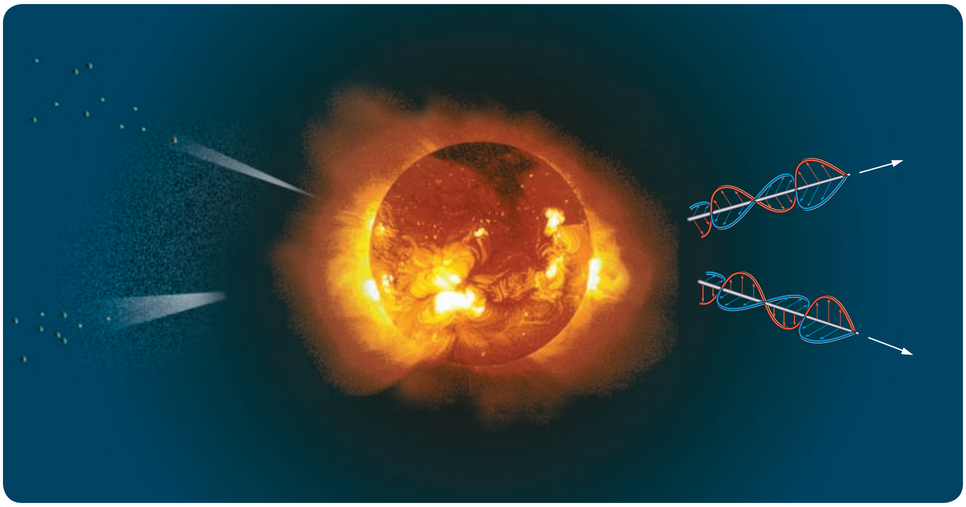
Imagine

walking between some shade trees early on a warm summer morning. Although the air is still cool, the effect of the sunlight is noticeable the instant you pass from a shaded spot to an area bathed in sunlight. Upon leaving the shadows, your eyes might automatically squint in response to the dramatic increase in the brightness of the light. Your skin would also detect a change as the Sun's rays create a warming sensation on exposed surfaces. If the day happened to be one with record-breaking high temperatures, the black asphalt pavement on roadways would absorb and then re-emit energy from the Sun for hours into the evening, long after the sun has set. Your eyes would not be able to detect this re-emitted radiant heat, but the thermal receptors in the skin on your fingertips could.

You have learned in previous courses that energy travels from the Sun to Earth through the near-perfect vacuum of space in the form of **radiation**. Recall that the radiation from the Sun is vitally important since it provides the essential input energy for virtually every food web and warms Earth so that the planet can be habitable. In Chapter 1 you learned about solar wind—radiation from the Sun in the form of particles with mass like electrons and protons.

radiation: energy emitted in the form of particles or waves

FORMS OF RADIATION FROM THE SUN

Type of Radiation	solar-wind particles	electromagnetic radiation
How Energy Is Transmitted		
Examples	fast-moving electrons, protons, and helium nuclei	visible light and radiant heat

The type of radiation that you can see with your eyes and sense as radiant heat with your skin does not involve particles with mass; instead, it is transmitted in the form of **electromagnetic radiation**, or **EMR**. Electromagnetic radiation consists of a changing electric field and a changing magnetic field travelling at right angles to one another. As you learned in Chapter 1, electric fields are produced by charged objects, whereas the source of all magnetic fields is moving charges. Electromagnetic radiation originates from accelerating charges.

In this lesson you will have an opportunity to survey the many forms of electromagnetic radiation. You may be surprised at how many everyday devices utilize electromagnetic technologies.

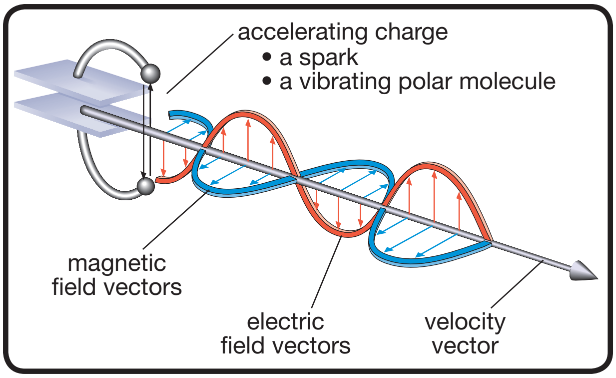


Figure C2.2: Electromagnetic radiation

electromagnetic radiation (EMR): a wave that consists of a changing electric field and a changing magnetic field travelling at right angles to one another

Practice

Use the table "Forms of Radiation from the Sun" to answer questions 1 and 2.

1. A straight line drawn from the centre to the perimeter of a circle is called a radius. Suggest an explanation for the origins of the word *radiation*.

2. In Chapter 1 you learned that in addition to solar wind, astronauts need to be protected from cosmic rays. Cosmic rays are large, positively charged particles emitted from stars in distant parts of the galaxy.

  a. Explain whether or not cosmic rays can be classified as a type of electromagnetic radiation.

  b. Describe evidence from your own experiences that supports the idea that distant stars emit electromagnetic radiation that travels to Earth.

Transmitting Energy Through Vibrations

Carefully examine Figure C2.3. The idea that waves transmit energy from one place to another through vibrations is demonstrated in the photograph.

The child's splashes disturb the surface of the water. As the water's surface returns to equilibrium, vibrations are set up in the form of ripples. The ripples transmit energy away from the child along the water's surface. In a similar way, the larger waves behind the child could be transferring energy from a boat far offshore.

Above the water, the child's voice disturbs the molecules in the air and causes a pattern of vibrations to carry sound waves away from the child through the air. As the sound energy reaches the ears of other people on the beach, they might turn in the direction of the source.

In the background of the photo, electromagnetic radiation from the setting Sun warms everyone on the beach and provides the last hours of daylight. These waves are different from the sound waves and the water waves because, in this case, the wave energy is not transmitted by vibrating matter.

When it comes to electromagnetic radiation, it's electric and magnetic fields that are doing the vibrating. You know from your work in Chapter 1 that these fields are invisible and are not a form of matter. This is how the electromagnetic radiation is able to travel through the vacuum of space to Earth. If electromagnetic radiation required matter to carry the vibrations, the energy from the Sun would be unable to reach Earth. Since electric and magnetic fields can exist in matter as well as in a vacuum, the electromagnetic radiation is able to travel through the gases of Earth's atmosphere to the shore in the photograph.

Figure C2.3

Practice

Use the following information to answer questions 3 and 4.

As electric current passes through the filament of an incandescent light bulb, the resistance of the tungsten filament causes it to heat up and emit light. Nearly all the air has been removed from the bulb so that the extreme temperature of the filament will not cause the filament to burn. This type of light source is considered to be inefficient because only 10% of the electrical energy produces light energy. The other 90% of the input energy produces waste heat.

3. Identify ways in which your body could detect the electromagnetic radiation emitted by the light bulb.

4. Explain how electromagnetic radiation is able to travel from the filament to the surrounding glass if the air inside the bulb is almost completely removed.

Investigation

Electromagnetic Radiation Transfers Energy

Science Skills
✓ Performing and Recording
✓ Analyzing and Interpreting

Background Information

Some devices, like small calculators and garden lights, can be powered by a photovoltaic cell, which converts light energy into electrical energy. This technology can be used to build a detector that indicates the intensity of electromagnetic radiation.

Purpose

You will assemble and use a simple detector to explore the electromagnetic radiation emitted from an overhead projector.

Materials

- overhead projector set up with an equilateral prism by your teacher
- photovoltaic cell with two leads
- 2 test leads with alligator clips at each end
- digital multimeter
- "Electromagnetic Energy to Electrical Energy" handout

Procedure and Observations

step 1: Set up the digital multimeter to measure millivolts.

step 2: Connect one end of each test lead to the photovoltaic cell. Connect the other ends of each test lead to the digital multimeter, as shown in Figure C2.4.

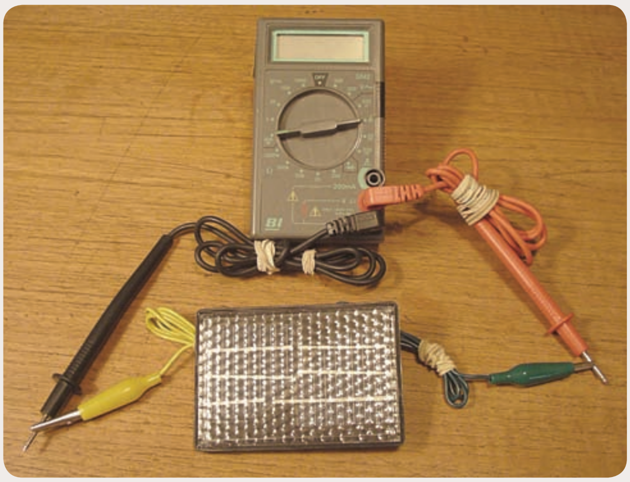


Figure C2.4

step 3: It is important to test the detector to ensure it is working. Bring the open face of the photovoltaic cell close to a light source and note how the display on the multimeter changes. Record your observations.

step 4: Obtain the handout "Electromagnetic Energy to Electrical Energy" from the Science 30 Textbook CD. You will record your results for the remaining steps on this handout.

step 5: Your teacher will turn on the projector with the prism and then turn off the lights in the room. You should see the white light from the projector being separated into all the colours of the rainbow on the screen.

step 6: Set the multimeter on its most sensitive setting. Place the photovoltaic cell in the violet region of the spectrum. Slowly move it toward the red end as you note the readings for each colour on the multimeter. Continue to move the photovoltaic cell beyond the red area until the values displayed on the multimeter reach a low value that no longer changes. Measure how far you were able to move into the dark area, away from the red region, to reach this point. Record the multimeter readings and your position on the handout.

step 7: Place the photovoltaic cell in the violet region of the spectrum and move it toward the area of darkness. Note the multimeter readings. Continue to move the apparatus until the signal reaches a low value that no longer changes. Measure how far you were able to move into the dark area to reach this point. Record the multimeter readings and your position on the handout.

Analysis

1. Describe how the multimeter readings changed as you moved the photovoltaic cell closer to a bright light source.

Refer to your observations on the handout as you answer the following questions.

2. Describe how the multimeter readings changed as you moved your detector
   a. through each colour of the spectrum
   b. into the dark region that borders the red region
   c. into the dark region that borders the violet region
3. The simple detector you built transforms electromagnetic energy into electrical energy. Use this fact to interpret your results from question 2 by describing how the intensity (strength) of the electromagnetic radiation changed in each case.
4. Your eyes are able to detect the electromagnetic radiation that produces all the colours of the rainbow. Describe the evidence from this investigation that suggests that your eyes are unable to detect all the electromagnetic radiation emitted by the projector.

Describing Electromagnetic Radiation

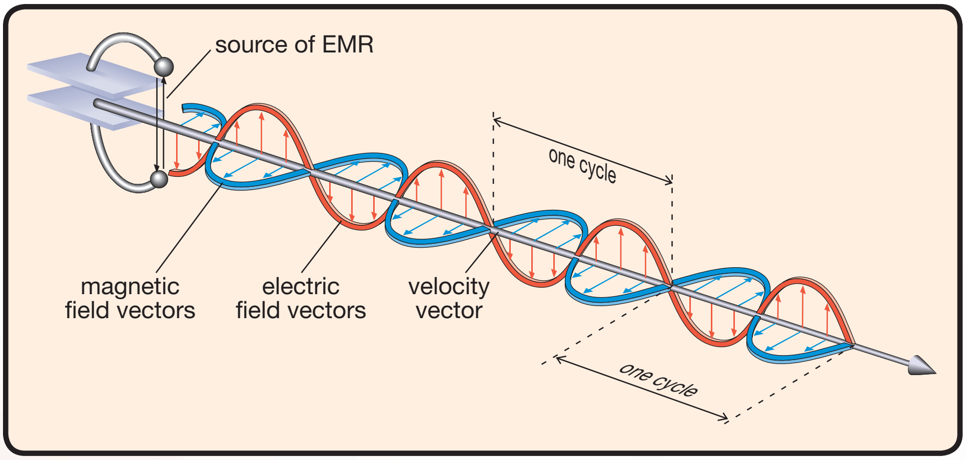


Figure C2.5: EMR is a transverse wave. The magnetic field vectors are at right angles to the velocity vector. The electric field vectors are at right angles to the velocity vector.

transverse wave: a wave in which the vibrations are perpendicular to the direction the wave is travelling

cycle: one complete vibration of a wave

wavelength: the distance from a point on one wave to the corresponding point on the next wave; the length of one cycle

Electromagnetic radiation can be described using the same terminology that you applied to other types of waves in previous courses. Electromagnetic radiation is a **transverse wave** because the direction of the vibrations is at right angles to the wave's direction of travel. Just like other transverse waves, electromagnetic radiation has crests and troughs. One **cycle** of the wave contains one crest and one trough of either the electric field vibration or the magnetic field vibration. A wave train is a series of many cycles and forms a repeating pattern of vibrations. The notion of a cycle is also important because it is central to two of the most important measurements used to describe a wave—wavelength and frequency.

Wavelength

The distance required for one complete cycle is a key characteristic of the wave. The length of one cycle is called the **wavelength**. In other words, wavelength is the distance from a point on one wave to the corresponding point on the next wave. The symbol for wavelength is the Greek letter *lamda*, λ.

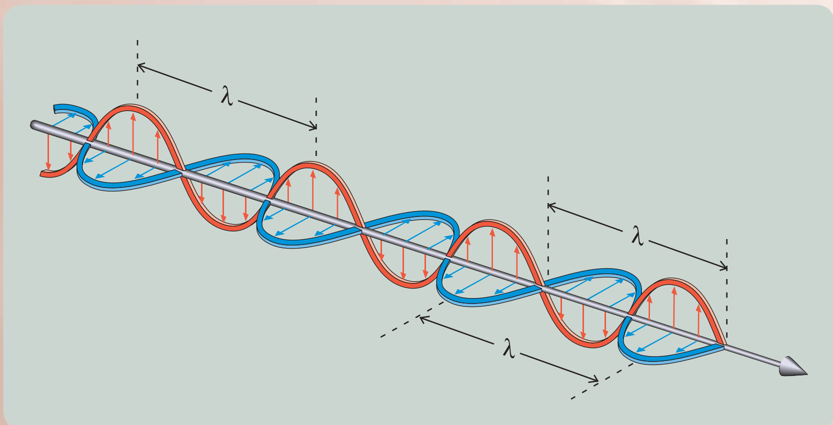
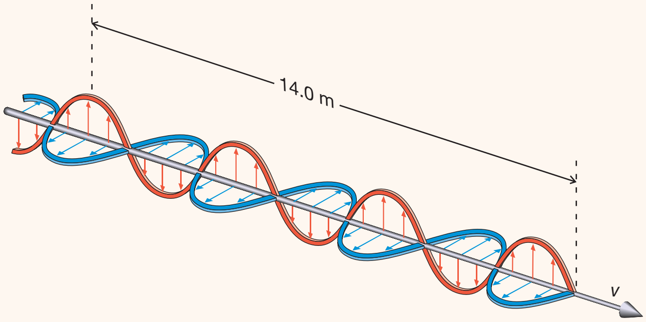


Figure C2.6: The wavelength, λ, of electromagnetic radiation can be measured in different ways.

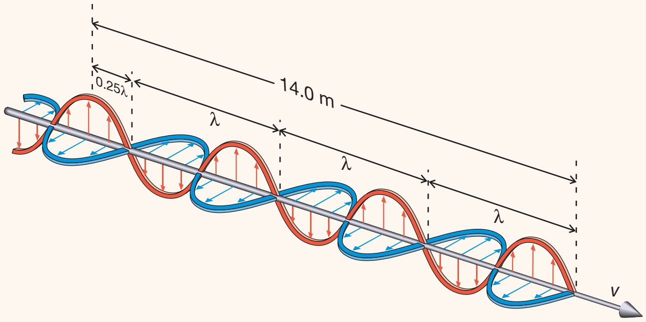
Example Problem 2.1

Determine the wavelength of this electromagnetic radiation.



Solution

step 1: Determine the number of wavelengths in the space.



There are 3.25 wavelengths in the space.

step 2: Calculate the wavelength of the EMR.

$$3.25\ \lambda = 14.0\ \text{m}$$

$$1\ \lambda = \frac{14.0\ \text{m}}{3.25}$$

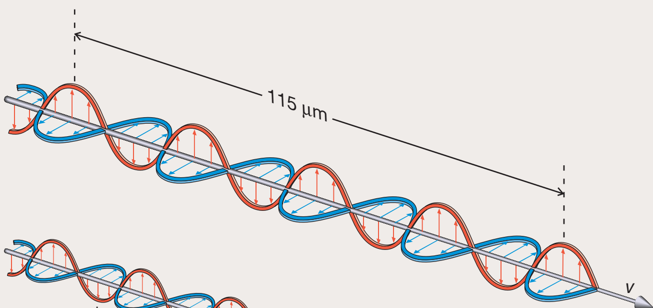
$$= 4.31\ \text{m}$$

The wavelength of this EMR is 4.31 m.

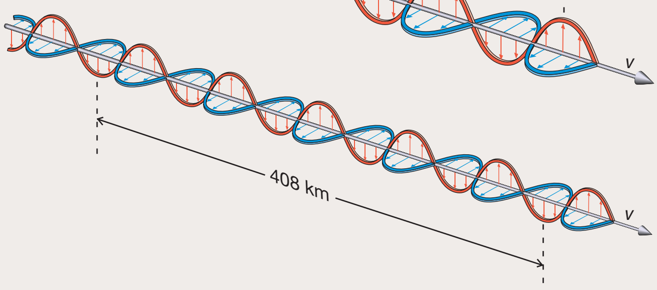
Practice

5. Determine the wavelength of the following examples of electromagnetic radiation.

a.



b.



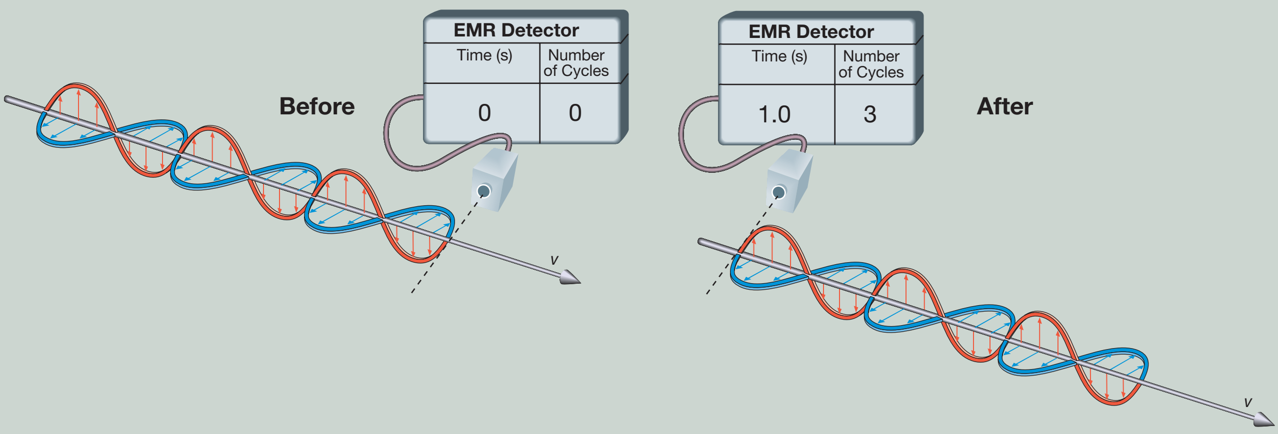
Frequency

Electromagnetic radiation can also be described in terms of how frequently a cycle passes a stationary point. This is known as the **frequency** of the wave. The symbol for frequency is f. If three cycles pass a point in one second, the frequency is said to be three cycles per second. To keep the communication more concise, "cycles per second" is simply called **hertz (Hz)**, in honour of Heinrich Hertz, who discovered radio waves. So, a frequency of three cycles per second is simply written as $f = 3$ Hz. If five cycles pass a point in a second, then the frequency is described as five cycles per second, or $f = 5$ Hz.

frequency: the number of cycles per second

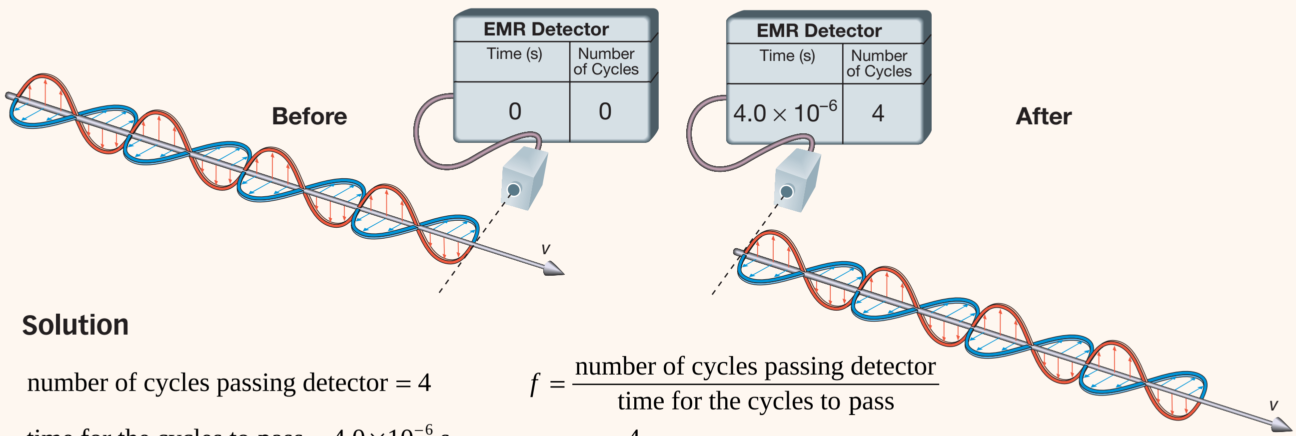
hertz (Hz): the unit for frequency

Three Cycles of an Electromagnetic Wave Pass a Detector



Example Problem 2.2

The following diagram shows an illustration of an electromagnetic radiation passing a detector. Use this information to determine the frequency of the EMR.



Solution

number of cycles passing detector = 4

time for the cycles to pass = 4.0×10^{-6} s

$f = ?$

$$f = \frac{\text{number of cycles passing detector}}{\text{time for the cycles to pass}}$$
$$= \frac{4}{4.0 \times 10^{-6}\ \text{s}}$$
$$= 1.0 \times 10^{6}\ \text{Hz}$$
$$= 1.0\ \text{MHz}$$

The frequency of the EMR is 1.0 MHz.

Alternative Solution

If four cycles pass in 4.0×10^{-6} s, then one cycle passes in 1.0×10^{-6} s. That means, for every second, one million cycles pass. This gives a frequency of one million cycles per second, or 1.0 MHz.

Practice

6. Determine the frequency of the following examples of electromagnetic radiation.

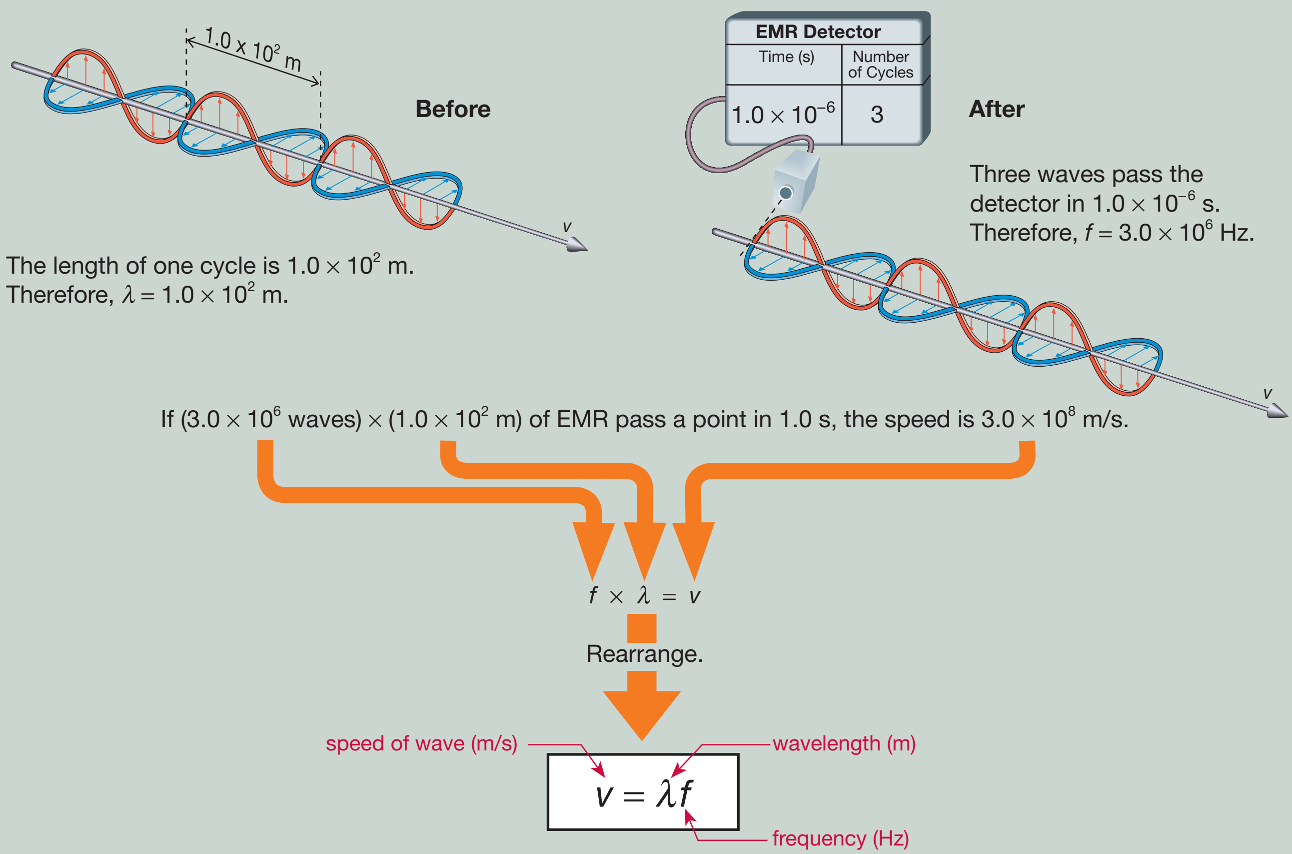
a. In 1.00 ms, 740 radio waves pass the antenna of a radio.

b. In 1.00 μs, 2450 microwaves pass through a point on a piece of cheese in a microwave oven.

Universal Wave Equation

The measurements of wavelength and frequency not only describe key characteristics of waves, they also provide a very convenient way to calculate the speed of the wave.

Illustrating the Universal Wave Equation



Universal Wave Equation

The equation $v = \lambda f$ is called the universal wave equation because it applies universally to all types of waves. When it comes to electromagnetic radiation, there is a very wide range of wavelength and frequency values, but the speed of all these waves when travelling through a vacuum is always the same, 3.00×10^8 m/s (the speed of light). This particular speed value has a special significance in science; so, it is given its own symbol, c. That's why the universal wave equation is often written as $c = \lambda f$ when it involves electromagnetic radiation. The speed of light is not always mentioned in problems involving electromagnetic radiation. It is important to remember the value of c or to be able to find it in the Science Data Booklet or some other resource.

Example Problem 2.3

An excited atom in a neon sign emits electromagnetic radiation with a wavelength of 6.4×10^{-7} m.

a. Calculate the frequency of the electromagnetic radiation.

b. If the neon sign was located 25.0 m from an observer, how long would it take the light from the sign to reach the observer?

Solution

a. $\lambda = 6.4 \times 10^{-7}$ m

$v = c = 3.00 \times 10^{8}$ m/s

$f = ?$

$$c = \lambda f$$

$$f = \frac{c}{\lambda}$$

$$= \frac{3.00 \times 10^{8}\ \text{m/s}}{6.4 \times 10^{-7}\ \text{m}}$$

$$= 4.7 \times 10^{14}\ 1/\text{s}$$

$$= 4.7 \times 10^{14}\ \text{Hz}$$

The frequency of the EMR is 4.7×10^{14} Hz.

b. $\Delta d = 25.0$ m

$v = c = 3.00 \times 10^{8}$ m/s

$\Delta t = ?$

$$v = \frac{\Delta d}{\Delta t}$$

$$\Delta t = \frac{\Delta d}{c}$$

$$= \frac{25.0\ \text{m}}{3.00 \times 10^{8}\ \text{m/s}}$$

$$= 8.33 \times 10^{-8}\ \text{s}$$

The light would take 8.33×10^{-8} s to travel from the sign to the observer.

Example Problem 2.4

The antenna of a FM radio station broadcasts electromagnetic radiation with a frequency of 104.5 MHz. A driver in a car is receiving these FM radio waves while travelling down a highway at 90.0 km/h, or 25.0 m/s.

a. Calculate the wavelength of the electromagnetic radiation.

b. Some of the FM radio waves can leave Earth's atmosphere and travel into space. Calculate how long it would take these radio waves to reach the Moon, which is located about 3.84×10^{8} m from Earth.

c. Use your answer to part b. to determine how far the car would travel in the same time it takes the radio wave to travel from Earth to the Moon.

Solution

a. $f = 104.5$ MHz

$= 104.5 \times 10^{6}$ Hz

$= 104.5 \times 10^{6}$ 1/s

$v = c = 3.00 \times 10^{8}$ m/s

$\lambda = ?$

$$c = \lambda f$$

$$\lambda = \frac{f}{c}$$

$$= \frac{104.5 \times 10^{6}\ 1/\text{s}}{3.00 \times 10^{8}\ \text{m/s}}$$

$$= 0.348\ \text{m}$$

The wavelength of the EMR is 0.348 m.

b. $\Delta d = 3.84 \times 10^{8}$ m

$v = c = 3.00 \times 10^{8}$ m/s

$\Delta t = ?$

$$v = \frac{\Delta d}{\Delta t}$$

$$\Delta t = \frac{\Delta d}{v}$$

$$= \frac{3.84 \times 10^{8}\ \text{m}}{3.00 \times 10^{8}\ \text{m/s}}$$

$$= 1.28\ \text{s}$$

The FM radio wave would take 1.28 s to travel from Earth to the Moon.

c. $\Delta t = 1.28$ s

$v = 25.0$ m/s

$\Delta d = ?$

$$v = \frac{\Delta d}{\Delta t}$$

$$\Delta d = v\Delta t$$

$$= (25.0\ \text{m/s})(1.28\ \text{s})$$

$$= 32.0\ \text{m}$$

The car would travel 32.0 m in the same time that it takes the radio wave to travel from Earth to the Moon.

Practice

7. An AM radio station broadcasts on a frequency of 960 kHz.

a. Calculate the wavelength of this electromagnetic radiation.

b. If a city block is about 100 m long, approximately how many city blocks would it take to contain one wavelength of this electromagnetic radiation?

8. Digital cellphones operate by sending and receiving electromagnetic radiation with a wavelength of about 16.5 cm.

a. Determine the frequency of the electromagnetic radiation emitted by a digital cellphone.

b. Determine your height in metres; then calculate how many wavelengths from a digital cellphone could fit in the space between your feet and the top of your head.

The Electromagnetic Spectrum

The complete range of all electromagnetic radiation is called the **electromagnetic spectrum**. The types of waves are usually organized according to wavelength and frequency.

electromagnetic spectrum: the wide band of different types of electromagnetic radiation ranging from radio waves to gamma rays

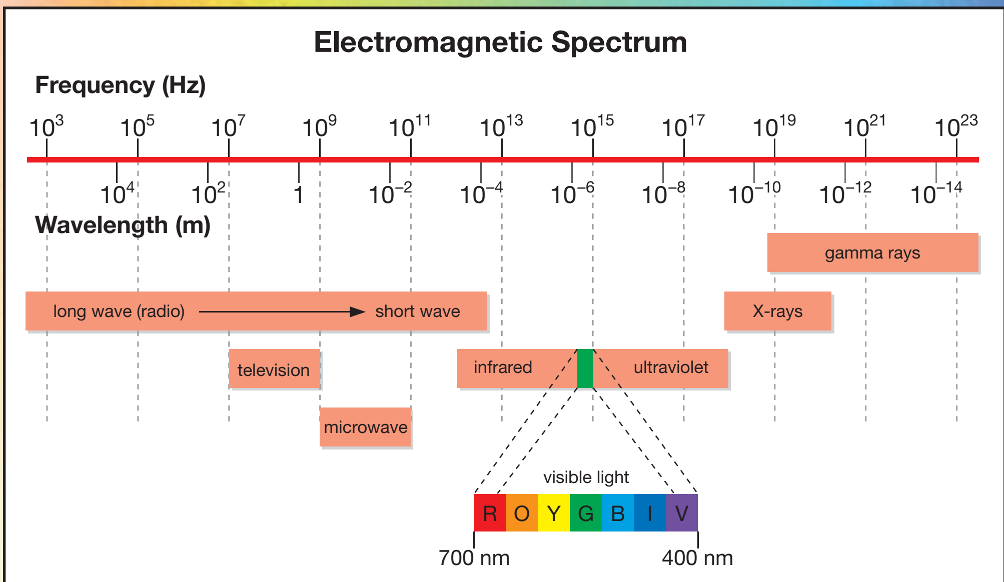


Figure C2.7: The electromagnetic spectrum

Note that some of the individual bands of electromagnetic radiation overlap one another. This is because the same type of electromagnetic radiation can be used to accomplish a number of very different tasks. As an example, waves with a frequency between 10^9 and 10^{11} Hz can be used for both communication (classified as radio waves) and for radar (classified as microwaves). The best way to understand how the individual bands on this chart relate to one another is to look at three key characteristics:

- the nature of the source for each band
- the energy transmitted by each band
- the effects of each band on living tissue

Radio Waves

Radio waves have the lowest frequency of all types of electromagnetic radiation because they are produced by the low-frequency vibrations of electrons within electric circuits. The ability of these waves to travel through the atmosphere makes them ideally suited for communication. However, the inability of radio waves to penetrate metal objects means that an external **antenna** is often required.

Figure C2.8: The antenna on this tower broadcasts radio waves into the surrounding countryside.

When a radio wave passes the antenna of a receiver, the vibrating electric fields within the wave cause electrons within the antenna to vibrate as well. The circuitry attached to the antenna decodes this electric signal, providing the user with the radio or TV broadcast. Since many radio waves can be received by the same antenna, the circuitry must allow users to select the particular frequency used by the station they wish to listen to or watch.

The effects of radio waves on living tissue vary, depending upon the specific frequency or wavelength. Radio waves with the lowest frequency are called **extremely low frequency** waves, or **ELF** for short. These radio waves are emitted from the 60 Hz of AC current found in household wiring and from power lines. It is unclear whether these waves have any effect on human health.

- **radio wave:** a type of electromagnetic radiation with a frequency less than 3000 GHz; used primarily for communications
- **antenna:** a transmitter or receiver of electromagnetic energy
- **extremely low frequency (ELF):** electromagnetic radiation with a frequency between 3 and 300 Hz; emitted from power distribution cables
- **magnetic resonance imaging (MRI):** a method of obtaining internal images of objects, especially living organisms, by using radio waves and strong magnetic fields

Radio waves with a wavelength of about 4 m are used with strong magnetic fields in **magnetic resonance imaging** (**MRI**) machines to produce detailed images of the inside of the human body. When these radio waves are directed at a specific body part, the nuclei of the hydrogen atoms in that body part give off energy, which is used by a computer to create an image. These particular radio waves are chosen for this purpose because they appear to have no harmful effects on the body. This lack of effects is thought to be due to the generally low energy content of these waves.

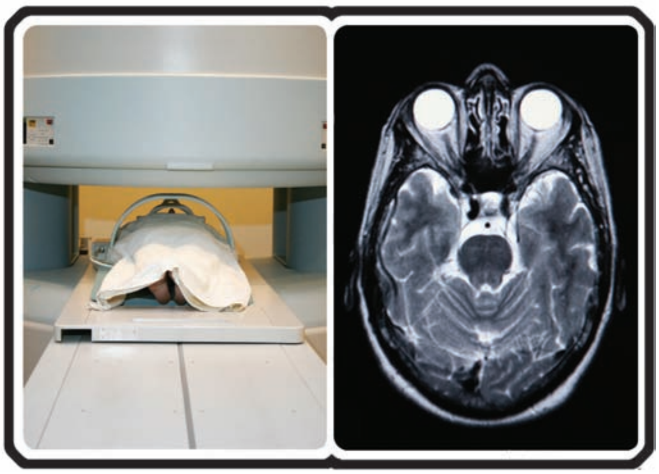


Figure C2.9: A magnetic resonance imaging, or MRI, machine uses radio waves to produce images of internal body parts.

Practice

9. Identify which part of a radio wave causes electrons in a car's antenna to vibrate.
10. In Chapter 1 you learned that metal objects can shield both electric and magnetic fields.
    a. Explain why a car's antenna must be located outside the car or built into the windshield.
    b. Explain why a car's radio is momentarily unable to receive a signal when the car travels under a highway overpass.
11. Many people enjoy speculating about the possibility of intelligent life inhabiting planets that orbit stars other than the Sun. It has been estimated that the first television shows broadcast in the mid-1900s would take about 50 years to reach all of the planets orbiting the nearest 400 stars to Earth. Estimate how far a radio wave containing a TV signal could travel in 50 years.

Microwaves

Although **microwaves** overlap with very short wavelength radio waves, they are usually classified as a distinct category because they generally transmit more energy than radio waves. To produce the desired high-frequency radiation of microwaves, high-frequency circuits are used. These circuits require special vacuum tubes to create microwaves.

microwaves: a type of electromagnetic radiation with a frequency between 1 GHz and 100 GHz; used for radar, satellite communications, and cooking food

The tube in Figure C2.10 is from a microwave oven. It is specially designed to produce electromagnetic radiation with a frequency of 2450 MHz. This frequency is best for causing water molecules to increase their molecular motion and to start rotating within the changing electric field of the microwaves. The result is that the rotating water molecules increase the molecular motion of other molecules in the food, causing a temperature increase. Similar heating effects also occur when microwaves interact with fat or sugar molecules, but the fastest cooking occurs when the food has a high water content.

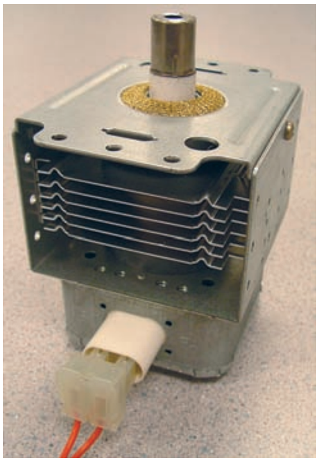


Figure C2.10

Figure C2.11: Whole eggs can explode when heated in a microwave oven. This is due to the buildup of steam within the egg's shell.

Since living tissue contains a high percentage of water molecules, the effects of microwaves on living tissue can be hazardous, particularly to those tissues that form the lens of the eye. There is evidence that prolonged exposure to microwaves leads to cataracts later in life.

Higher-frequency microwaves (ones that are not absorbed by water molecules) are used in telecommunications because they are particularly effective at penetrating through rain, snow, haze, and smoke. This makes microwaves ideally suited for radar applications and satellite communications.

DID YOU KNOW?

The global positioning system (GPS) is a system of Earth-orbiting satellites that can provide information about the exact location of anyone with a GPS receiver. Each satellite transmits microwave signals that are modulated by timed pulses. When pulses are received from four or more other satellites, an inexpensive GPS receiver can determine positions on Earth with an accuracy of ± 5 m.

Practice

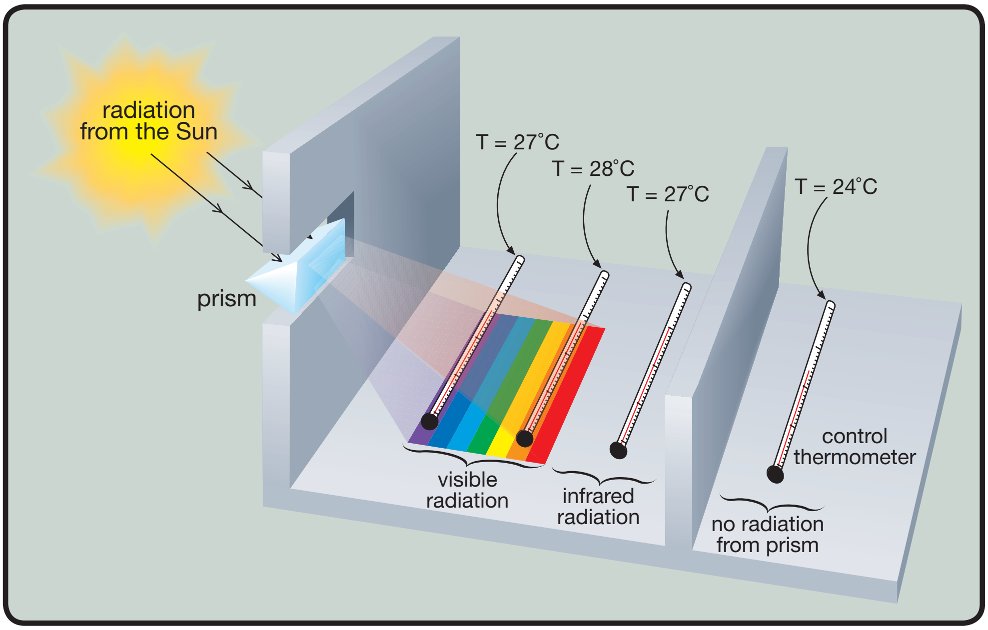
12. If microwave ovens use electromagnetic radiation with a frequency of 2450 MHz, calculate the wavelength of the microwaves.

13. Explain the following statement.

When reheating a plate of food in a microwave oven, it is important not to leave a metal fork on the plate. The metal fork will act as an antenna for the microwaves in the oven, resulting in dangerous sparking.

Infrared Radiation

When sunlight passes through a prism, it is separated into all the colours of the rainbow. If thermometers with blackened bulbs are placed in the coloured region of the spectrum, the temperature increases relative to a control thermometer that is shielded from the prism. These temperature increases indicate that visible light transfers energy. If a thermometer is placed in the dark area beside the red region, it shows an increase in temperature as well. Even though there is no visible light in this area, the thermometer indicates that energy is being transmitted. When this experiment was first done in 1800, the conclusion was that an invisible form of light was separated from the sunlight by the prism. Today, this light is called **infrared light** or **infrared radiation**. The word *infra* is Latin for "below." As the name suggests, infrared light has a frequency just below red.



infrared light or infrared radiation: a type of electromagnetic radiation, with a frequency between 3.0×10^{11} Hz and 4.3×10^{14} Hz, that increases the vibrations between molecules, resulting in heating effects

There is a range of electromagnetic radiation that is classified as infrared. The temperature-sensitive nerve endings in your skin can detect infrared waves. So, when you feel the warmth of a campfire, you are sensing infrared radiation. The remote controls you use with TVs and DVD players also use infrared radiation. Your skin is not able to detect the heating effects of the infrared waves produced by a remote control; but, as indicated in the "Exploring Coded Signals" activity, these waves can still transfer energy.

Infrared radiation is emitted by the vibration or rotation of the molecules within a material; so, objects that are warm or hot tend to emit energy in the infrared part of the electromagnetic spectrum. It is advantageous for humans and most other animals to be able to sense infrared radiation—objects that emit infrared radiation tend to be hot and may represent a burn hazard.

Practice

14. In addition to being able to detect infrared radiation, humans are also sources of infrared radiation. Most people emit a band of infrared radiation with a peak wavelength of about 10 μm.

a. Explain the mechanism that allows the human body to emit this radiation.

b. Calculate the frequency of this radiation.

15. Sunlight pours in through a window as two friends watch a football game on television. A hot bowl of popcorn sits between them as they use the remote control to switch between games on different channels.

a. Identify the sources of infrared radiation.

b. If the TV is operated by an infrared remote control, how does the circuitry within the TV distinguish between the signal from the remote control and the infrared radiation generated by other objects in the room?

Using Infrared Radiation for Communication

Handheld computers (PDAs) are a popular way for working people to stay in touch with their e-mail accounts, scheduling software, and customer-account information when they are away from the office. These devices are able to send and receive signals with other devices, such as printers, laptop computers, cellphones, digital cameras, and other handheld computers.

Since most of the radio-wave frequencies are already heavily used, many of these devices communicate using an encoded infrared signal. This form of communication is often called **beaming**. In the next investigation you will have an opportunity to explore some of the characteristics of this technology by building a simple infrared transmitter and receiver.

beaming: the communication of data between wireless devices using a beam of infrared light

Investigation

Building and Testing an Infrared Transmitter and Receiver

Science Skills

✓ Performing and Recording

✓ Analyzing and Interpreting

Purpose

You will build and test a simple infrared transmitter and receiver.

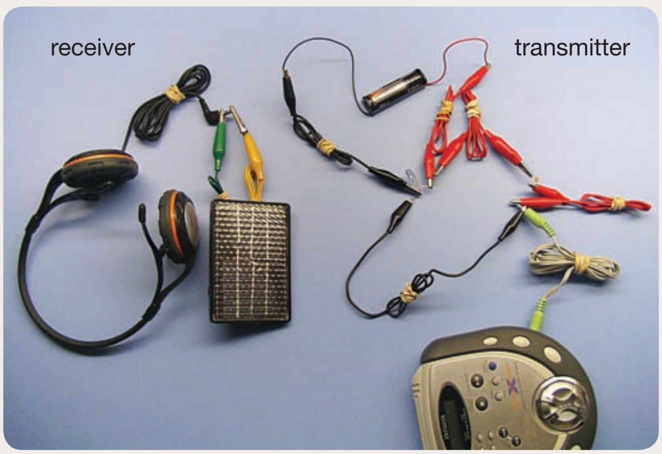
Materials

- portable music system with a headphone jack (e.g., CD player or MP3 player)
- set of sensitive headphones for the portable music system
- 7 test leads with alligator clips at each end
- 7 small elastic bands to shorten the test leads
- 1 AA cell in a holder with leads
- photovoltaic cell with leads
- infrared LED (light-emitting diode) with peak wavelength of 940 nm
- 0.22-μF capacitor (50 WVDC max)
- audio cable with 3.5 mm ($\frac{1}{8}$-inch) stereo plugs at each end (must be less than 2 m long)
- infrared remote control
- 6 sheets of facial tissue
- "Building an Infrared Transmitter and Receiver" handout

Procedure and Observations

Part A: Building the Infrared Transmitter and Receiver

Obtain the handout "Building an Infrared Transmitter and Receiver" from the Science 30 Textbook CD. Follow the instructions in this handout to build the transmitter and receiver.



Part B: Testing the Infrared Transmitter and Receiver

Procedure and Observations

step 1: Determine how the equipment should be arranged to produce the strongest signal between the transmitter and the receiver. Record your results.

step 2: While listening through the headphones, slowly pull the photovoltaic cell away from the LED to determine the maximum distance that the receiver is able to receive a useable signal from the transmitter. Record your results.

step 3: Determine how many sheets of facial tissue are required to absorb the infrared energy from the transmitter when the photovoltaic cell is located 8.0 cm from the LED.

Analysis

1. Suppose the transmitter and receiver you built in this investigation were the prototype for a new model of wireless communication technology. Use the results of this experiment to write a concise summary that describes some of the strengths and weaknesses of your infrared transmitter and receiver as a communication technology.
2. Use the Internet as a tool to gather information about the strengths and weaknesses of commercially available infrared communication technologies.

Visible Light

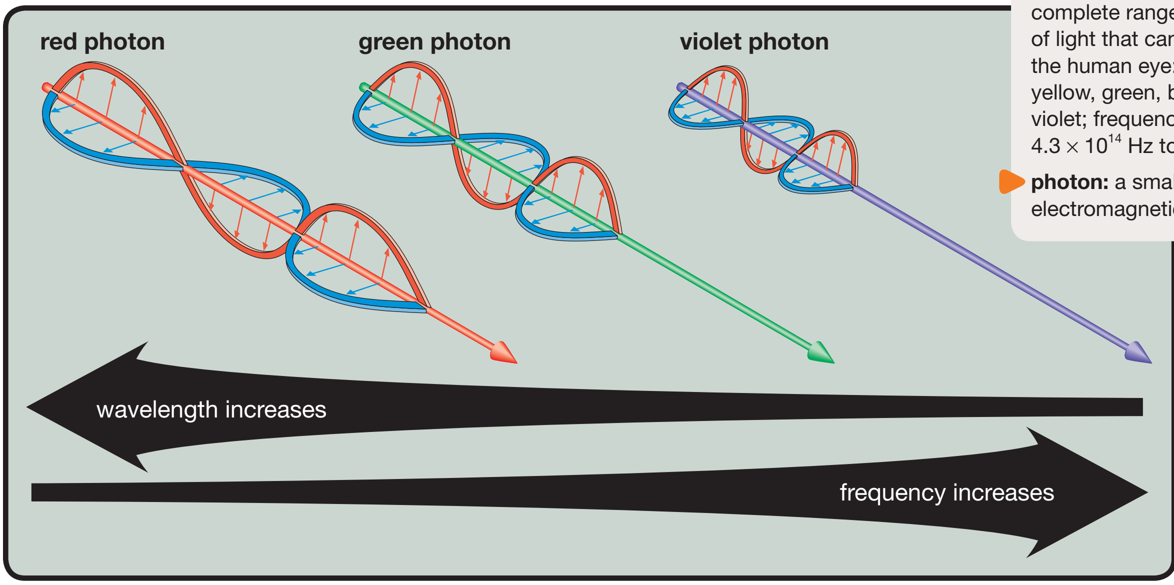
In the entire electromagnetic spectrum, the colours red through violet make up a very thin slice called the **visible spectrum**. Many students use the name "**Roy G Biv**" as a memory device to help them remember the order of all the colours in the visible spectrum: **r**ed, **o**range, **y**ellow, **g**reen, **b**lue, **i**ndigo, and **v**iolet. Individuals have different abilities to see colours. For most people, the limits of vision extend from radiation with a wavelength of about 700 nm at the red end to about 400 nm at the violet end.

In general, visible light is emitted by objects that are hot: the filament of a light bulb, the flame of a candle, or the surface of the Sun. In all cases, the temperature is high enough to cause electrons to jump within the overlapping energy levels of closely packed atoms or molecules.

Just over 100 years ago, at the beginning of the twentieth century, Albert Einstein proposed a radical adjustment to the idea that visible light was an electromagnetic wave. Einstein proposed that although light had a wavelength and a frequency, it was not emitted in long trains of connected waves. Instead, it was emitted in bundles of energy called **photons**. A photon can behave like a particle in that it can collide and interact with an individual atom, but it has no mass because it is a tiny packet of electromagnetic energy. The energy of an individual photon depends upon the frequency of the radiation—the higher the frequency, the greater the energy of the photon. In the visible spectrum, red photons have the least amount of energy, while violet photons have the most.

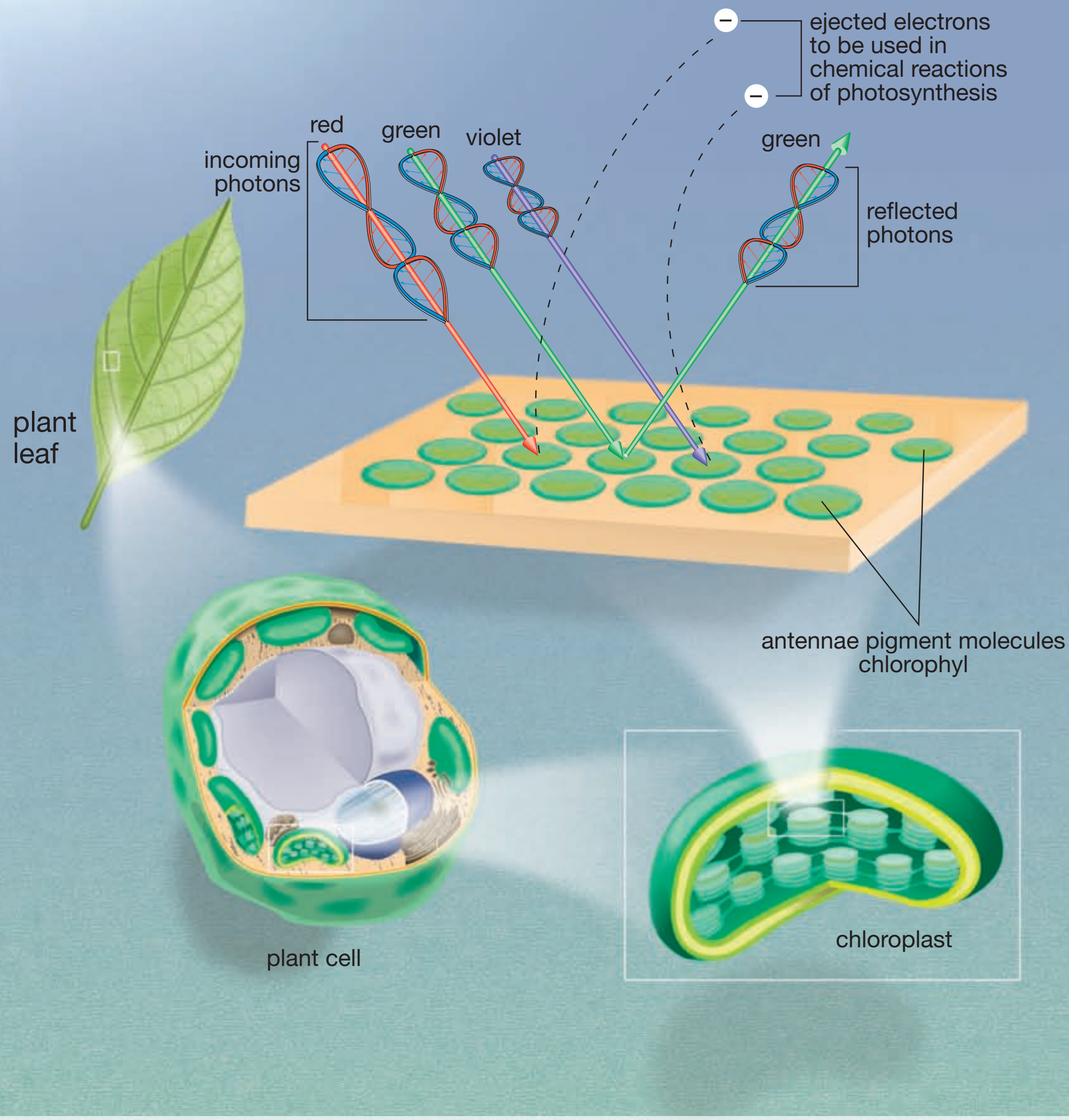
visible spectrum: the complete range of all colours of light that can be seen by the human eye: red, orange, yellow, green, blue, indigo, and violet; frequencies range from 4.3×10^{14} Hz to 7.5×10^{14} Hz

photon: a small bundle of electromagnetic energy



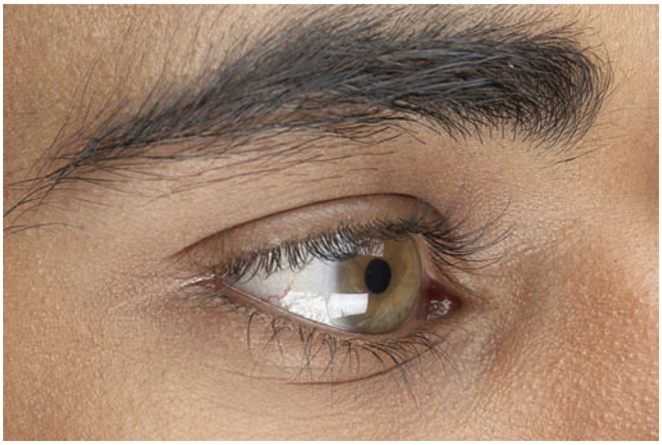
Photosynthesis

One of the best illustrations of the photon model of light is photosynthesis. The input energy for this process is visible light energy from the Sun. Within the cells on the leaf of a green plant, a specialized structure called a chloroplast contains the pigment molecules called chlorophyl. The pigment molecules act like antennae—discs spread out in horizontal patterns to absorb as much energy from the incoming photons as possible.



Note that the chlorophyl molecules absorb the energy in the photons of red and violet light—using this energy to eject electrons. These electrons are then picked up by other molecules that participate in the chemical reactions of photosynthesis.

The photons of green light are not absorbed because they do not have the exact amount of energy needed to eject electrons in the chlorophyl molecules. You could say that the chlorophyl "antennae" are not "tuned" to this particular frequency of electromagnetic radiation. Since green-light photons are not absorbed, the energy is reflected. This is why a plant leaf looks green under white light: the light from the red and violet ends of the visible spectrum has been absorbed, leaving only the light from the middle of the visible spectrum—green—to be reflected to your eyes.



Photosynthesis is just one example of how photons of visible light interact with living tissue. The reactions that occur as photons strike the retina are similar. In both cases, the energy of the photons is sufficient to cause an electron to be ejected from a specialized receptor molecule, but the energy is not so great that irreversible chemical changes occur. As you will see later in this lesson, if photons with more energy than visible light strike these cells, permanent damage can occur.

Although Einstein's photon model for light applies to the whole electromagnetic spectrum, the effects have practical applications only for radiation with frequencies close to visible light or higher. At the radio-wave end of the spectrum, continuous wave effects dominate—radio-wave photons would be very difficult to detect. At the gamma-ray end of the spectrum, the particle-like behaviour of photons is most significant, while continuous wave effects are difficult to detect. Visible light is positioned in the middle of the spectrum, so it is ideal for demonstrating the unique blend of both continuous wave and photon characteristics.

Practice

16. Identify the types of sources that produce visible light.

17. Compare and contrast a photon of red light with a photon of violet light.

18. Why do the leaves of most plants look green?

19. Use the words *photon*, *antenna*, and *chlorophyl* to explain why green plants tend to turn their leaves toward a light source.

Ultraviolet Radiation

The Latin word for "beyond" is *ultra*, so it shouldn't be surprising that the radiation that has a frequency just beyond violet is called **ultraviolet light**, **ultraviolet radiation**, or just **UV**. Ultraviolet photons are emitted from sources that are very hot—hotter than the sources for visible light. Some people refer to an ultraviolet light source as a "black light," but the word *black* means the absence of light, so this is not really an accurate description. The best way to think of ultraviolet light is in terms of photons. Since ultraviolet photons have a higher frequency than those in the visible spectrum, they have more energy.

ultraviolet light, ultraviolet radiation, or UV: a type of electromagnetic radiation that is emitted by very hot objects; frequencies range from 7.5×10^{14} Hz to 1×10^{18} Hz

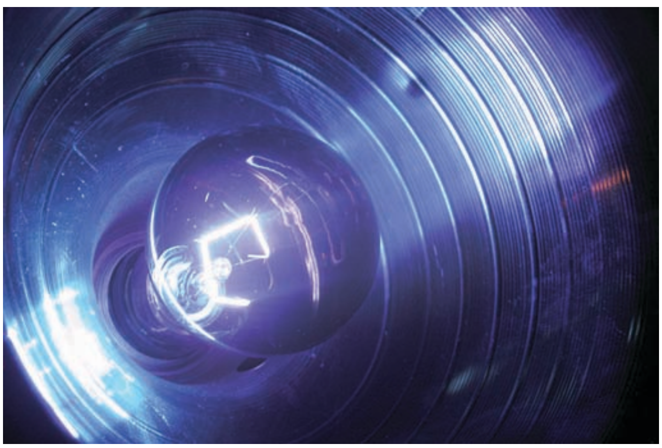
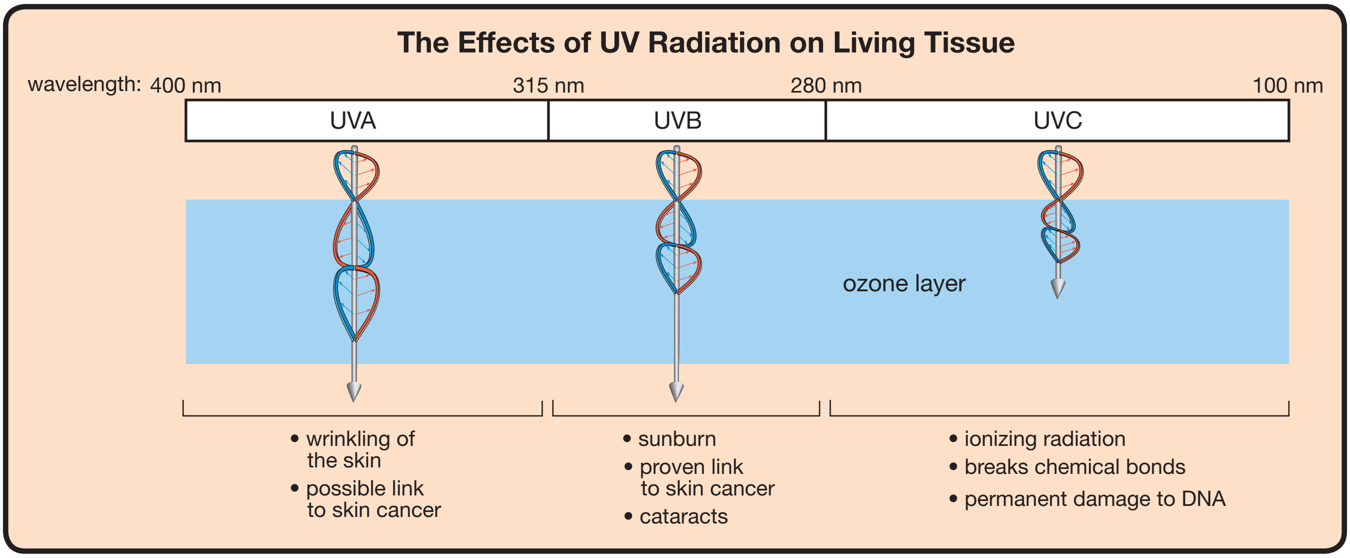


Figure C2.12: This lamp emits both visible light and ultraviolet radiation.

Figure C2.13: Good-quality goggles used for snowboarding and skiing have special coatings to absorb ultraviolet radiation.



In terms of wavelength, the ultraviolet band spans from 400 nm down to 100 nm. This band can be divided further into UVA, UVB, and UVC. You will likely run across these terms on product labels when shopping for sunglasses or goggles for outdoor activities. It's important to ensure that the sunglasses or goggles you buy will stop 100% of the UVA and UVB radiation from entering your eyes. High-energy photons can do permanent damage to living tissues. UVC photons are even more hazardous, but Earth's ozone layer absorbs most of the UVC radiation before it reaches Earth's surface.

Photons of UVC radiation have so much energy that they eject electrons from atoms, ionizing the atoms and leading to the formation of free radicals. As you learned in Unit B, free radicals are highly reactive particles that accelerate the decomposition of organic compounds. This is why UVC is classified as a type of **ionizing radiation**. When a UVC photon collides with a molecule of DNA, the ionization triggers the formation of free radicals, which causes one of the DNA strands to break.

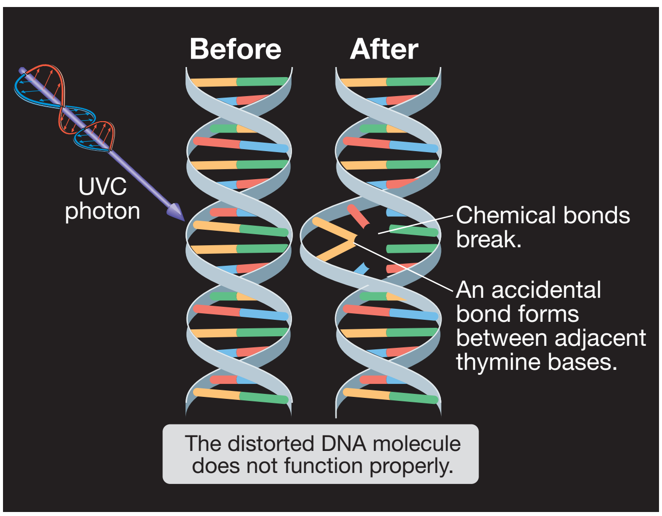


Figure C2.14

As shown in Figure C2.14, a UVC photon can break chemical bonds and cause an accidental bond to be formed between adjacent bases. The DNA molecule becomes distorted and is no longer able to replicate properly. If this kind of event happens in several places along the DNA of a bacterium, the micro-organism is no longer able to replicate its DNA. It dies or will be unable to reproduce. This is the basis of technologies that use ultraviolet radiation to sterilize medical and laboratory tools.

Figure C2.15: Most schools use cabinets like this to sterilize safety goggles with UVC light. As a safety mechanism, the bulb that is the source of the radiation turns on only when the door is closed.

ionizing radiation: high-energy radiation capable of ionizing the material through which it passes, leading to the formation of free radicals

Effects of Long-Term Exposure to Radiation


Figure C2.16: Long-term exposure to UV light causes the skin to wrinkle, sag, and become leathery.

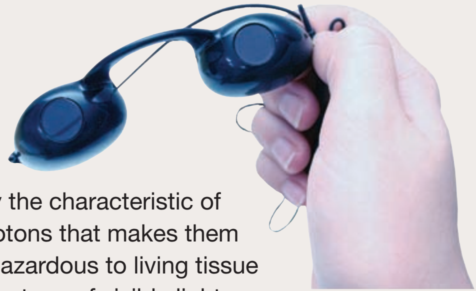
Many years of exposure to UV light from the Sun can lead to premature aging of the skin. Dermatologists explain to their patients that many forms of skin cancer can be traced back to accumulated damage to tissues that have been exposed to UV radiation since childhood. The medical evidence clearly indicates that long-term exposure to low doses of UV radiation can have negative effects on health. Researchers are currently investigating other areas of the electromagnetic spectrum to explore the connections between long-term exposure to low doses of radiation and illness.

Science Links

Many scientists suspect that skin cancers caused by exposure to UV light could become more of a problem in the future because a key component of the atmosphere that protects people from this radiation is being depleted. Most of the UV photons emitted by the Sun are absorbed by ozone in the stratosphere. As described in Unit B, human activities release compounds, such as CFCs, that reduce the concentration of ozone in the stratosphere.

X-rays: high-energy electromagnetic radiation with a frequency between 10^{18} and 10^{21} Hz; can be produced when fast-moving electrons strike a metal target

Practice



20. Identify the characteristic of UV photons that makes them more hazardous to living tissue than photons of visible light.

21. To help reduce UV damage to the skin, many people apply sunblock or a sunscreen before spending time in the sun. These lotions contain compounds that are specially designed to absorb different types of ultraviolet radiation:

- UVA absorbers—titanium dioxide, zinc oxide, and avobenzone
- UVB absorbers—homosalate, octyl salicylate, and octyl methoxycinnamate

a. Describe the health benefits of a sunblock that has homosalate as an ingredient.

b. Describe the health benefits of a sunblock that has zinc oxide as an ingredient.

c. If the most hazardous type of ultraviolet radiation is UVC, explain why there isn't an ingredient in sunscreen to block UVC rays.

X-rays

Annual dental checkups typically begin with diagnostic **X-rays** of your teeth. The patient in Figure C2.17 is wearing a lead apron and is temporarily holding the film in place while the X-ray machine is brought into position. Once everything is in place, the patient will remove her finger from her mouth and the technician will leave the area before the machine is switched on, emitting a momentary stream of X-rays. After the procedure is over, the lead apron is removed and the patient can then meet with the dentist, who carefully examines the images.

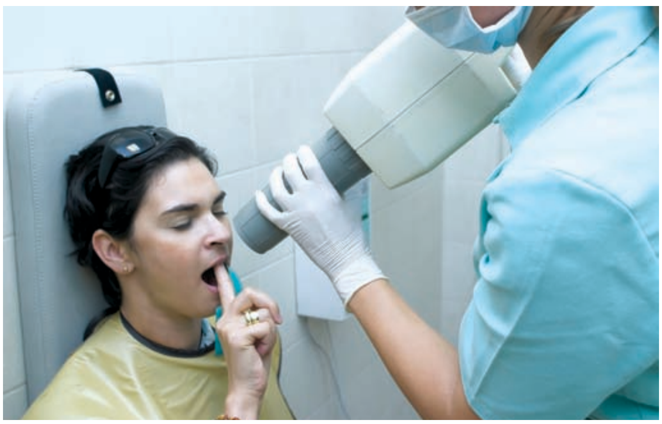
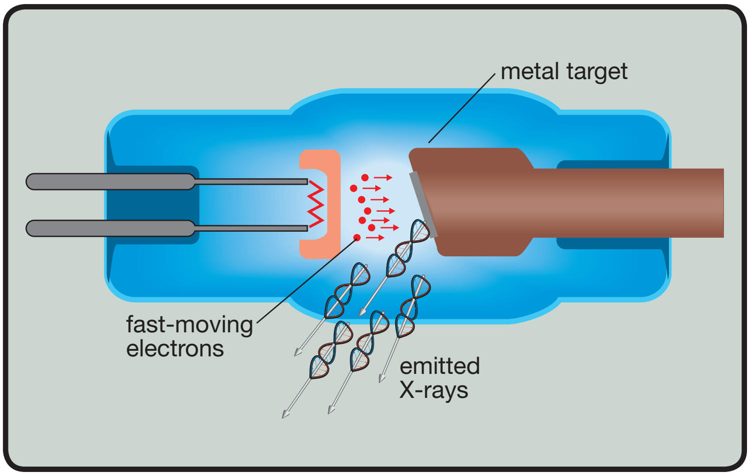


Figure C2.17

X-ray radiation can produce images of the insides of teeth or other body parts due to the fact that X-rays can penetrate some body tissues. The X-rays cause photographic film to be exposed by causing a chemical reaction to change the film from white to grey or black. The more dense tissues—like teeth, bones, and dental fillings—absorb more X-ray photons, so the film behind those areas appears white or lighter. Less dense tissues—like skin, fat, muscle, and blood vessels—appear darker on the film because more X-rays are able to pass through. A tooth that has a cavity or a crack allows more X-rays to pass through, so these features form darker areas on the image.



X-rays are produced using a high-voltage tube. The high voltage is used to give electrons high speeds so that they collide with a metal target, producing X-rays. The X-rays that leave the tube can travel from the tube through the air and then enter living tissue. When an X-ray photon collides with a molecule in a cell, a valence electron is knocked out of the molecule. Due to the high energy of the X-ray photon, the ejected electron leaves with a large quantity of kinetic energy, allowing it to ionize hundreds or thousands of other molecules in the area of the initial collision. Clearly, X-rays are a powerful form of ionizing radiation. When DNA is ionized by this kind of interaction, it is possible for both strands of the double helix to break. A double-strand break is much more difficult to repair than a single-strand break. If a fragment of DNA is lost during the repair process, the results can include mutations, chromosome aberrations, or the death of the cell. Given the effects of ionizing radiation on living tissue, you can see why it is so important to minimize your exposure to X-rays.

GUIDELINES FOR MINIMIZING EXPOSURE TO SOURCES OF IONIZING RADIATION

For the Safety of the Patient	For the Safety of the Technician
• Use the minimum photon energy to accomplish the task. • Use shielding to protect tissues not involved in the procedure, especially tissues with rapidly dividing cells. • Avoid exposing unborn children and infants to X-ray radiation.	• Reduce time spent near the source. • Increase distance from the source. • Use shielding between the source and the technician.

ALARA: As Low As Is Reasonably Achievable

Long-term exposure to low doses of ultraviolet light can create health problems later in life. The same can likely be said for long-term exposure to low doses of X-rays or any other form of ionizing radiation. The person or the body organ that is repeatedly exposed to low doses of radiation may survive, but the cells can become damaged. This damage can lead to cancer and other negative effects years after the initial exposure. Since current scientific evidence indicates that any radiation dose, no matter how small, may result in some negative effects on human health, it is best to keep the exposure to ionizing radiation as low as is reasonably achievable, or ALARA for short.

Rapidly dividing cells, like those that produce blood cells in bone marrow, are particularly vulnerable to the effects of ionizing radiation because these cells spend a large percentage of their time in the process of DNA replication. Recall from Unit A that the processes that run cell division involve the replication of DNA and the lining up of chromosomes before cell division. These processes inadvertently increase the chances for genetic damage by presenting a large target to the radiation for an increased period of time. Unborn children are especially sensitive to ionizing radiation because their cells are dividing at a high rate and are developing into different kinds of tissue.

Since rapidly dividing cells are the ones most susceptible to damage from ionizing radiation, it makes sense that X-rays can also be used to kill cancer cells. When a focused beam of radiation is used to shrink or eliminate cancerous tumours, the process is called **radiation therapy**. The goal of this cancer treatment is to kill the cancer cells while doing as little damage as possible to the surrounding tissue.

radiation therapy: the medical use of ionizing radiation to treat disease, especially forms of cancer

Gamma Radiation

One of the leading ways to treat a brain tumour is to target the tumour with beams of very high-energy photons emitted from the nuclei of **radioactive** materials. The material used in this machine is cobalt-60, a radioactive isotope produced in nuclear reactors. The special name for photons emitted from radioactive sources, like cobalt-60, is **gamma radiation**. Gamma photons have the highest frequency of all types of electromagnetic radiation. It follows, then, that gamma photons also have the highest energy and the greatest penetrating power. Gamma radiation overlaps X-rays in the electromagnetic spectrum. They both produce ionizing radiation and they have an exceptional ability to penetrate matter. The only real differences stem from the fact that gamma photons originate from the nuclei of radioactive materials and can have even higher frequencies than X-rays.

radioactive: a term used to describe substances that spontaneously emit radiation from unstable nuclei

gamma radiation: the highest energy form of electromagnetic radiation with frequencies above 10^{19} Hz; emitted from the nuclei of radioactive materials

Practice

Use the information below to answer questions 22 to 25.

Figure C2.18 shows a patient's X-ray after reconstructive surgery to repair a broken jaw. The same kind of panoramic X-ray is taken during orthodontic work.

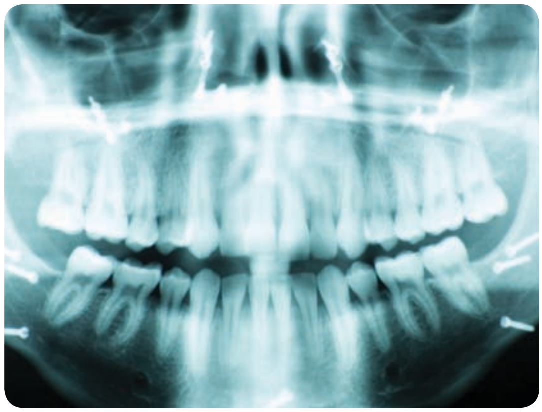


Figure C2.18

22. Explain why the tiny screws appear white in the image.

23. Closely examine the teeth on the lower left of Figure C2.18. Describe the evidence that supports the idea that these teeth have soft tissue, like nerves and blood vessels, inside them.

24. An X-ray machine produces photons with a frequency of 7.1×10^{18} Hz. Calculate the wavelength of these X-ray photons.

25. A woman slipped and fell on the ice while curling. She thinks that she may have injured her hip. Explain why it is important for the doctor to ask the woman if there is a possibility that she might be pregnant before recommending an X-ray be taken.

Utilizing Technology

Minimizing Exposure to Radiation

Science Skills
✓ Initiating and Planning
✓ Performing and Recording
✓ Communication and Teamwork

Purpose

You will use a questionnaire and other resources as you work with other students to develop strategies to minimize your exposure to radiation.

Part A: Ionizing Radiation

Background Information

Each day you are exposed to a number of different types of ionizing radiation. Some of the sources of radiation are unavoidable, while other sources could be classified as voluntary because they are due to decisions you have made about how you live your life. In this activity you will work with other students to identify strategies that will help keep your exposure to ionizing radiation as low as is reasonably achievable.

Procedure and Analysis

step 1: Obtain the handout "Questionnaire: Estimating Your Annual Dose of Ionizing Radiation" from the Science 30 Textbook CD. Complete this questionnaire, and add up the totals for each section as well as the grand total from all sources.

step 2: Compare your results from step 1 with the results of your classmates. Use the questionnaire to identify the sources that account for the differences in the results between individual students. Suggest strategies that could be used to minimize the exposure to radiation for students with higher scores.

Part B: Non-Ionizing Radiation—Radio Waves

Background Information

Since the 1990s there has been a dramatic increase in the amount of radiation in the form of radio waves that comes in contact with human tissue. Although there are many technologies that have contributed to this increase, the most significant is the growing popularity of handheld cellphones. Many people would argue that since radio waves are not a form of ionizing radiation, the health risks associated with the use of this technology are minimal. Others disagree, indicating that the high use of this technology could present a situation similar to the exposure to solar UV, where long-term exposure to low doses of radiation creates health problems, including cancer, many years after the initial exposure. Since so many people use cellphones, it is important to learn whether this source of radiation presents a health hazard—and to reassure the users of this technology if it does not.

Procedure and Analysis

1. Estimate the number of minutes you spend using a handheld cellphone every month. You may need to consult the monthly statement from your service provider. Compare your results with those of other students, and determine the average number of minutes of monthly cellphone use for your group. Use the average value for your group to estimate the total length of time that cellphones would be used in one year and in one lifetime.
2. Refer to the table "Guidelines for Minimizing Exposure to Sources of Ionizing Radiation" that was presented earlier in this lesson. Using the guidelines presented on this table, work with other students to develop a list of strategies that could be used to reduce the exposure to the radio waves produced by a cellphone. Identify the strengths and weaknesses of each strategy.
3. Work with members of your group to develop a list of specific questions that researchers should consider when designing experiments to investigate the possible connections between cellphone use and human health.
4. Perform an Internet search to determine some of the specific questions that researchers are currently investigating on the topic of cellphone use and human health. Compare the results with the list of questions you developed in question 3.

2.1 Summary

The electromagnetic spectrum includes a wide variety of electromagnetic radiation. When listed from lowest frequency to highest frequency, the spectrum includes radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. Visible light is the form of radiation that people are most familiar with because it includes all the colours that can be detected by the human eye: red, orange, yellow, green, blue, indigo, and violet. Visible light is uniquely positioned in the electromagnetic spectrum because it is able to demonstrate the wave characteristics of the radio-wave end of the spectrum and the photon characteristics of the gamma-ray end of the spectrum. Gamma rays, X-rays, and UVC are all classified as ionizing radiations because each of them can break chemical bonds, which triggers the production of free radicals.

2.1 Questions

Knowledge

1. Obtain the handout "Summarizing the Characteristics of the Electromagnetic Spectrum" from the Science 30 Textbook CD. Complete the table by adding rows for each type of electromagnetic radiation and by adding concise descriptions under each category. Note that you may have to continue the table on additional pieces of paper.

Applying Concepts

2. The X-rays used by a dentist to produce images of a patient's teeth have a frequency of 7.2×10^{18} Hz.
   a. Calculate the wavelength of these dental X-rays.
   b. Hydrogen is the smallest atom. When a hydrogen atom is unexcited, the orbit of the electron is about 5.29×10^{-11} m from the nucleus. Compare the wavelength of the dental X-ray to the radius of the electron's orbit for an unexcited hydrogen atom.
3. A GPS satellite emits two microwave signals: one with a wavelength of 19.0 cm and the other with a wavelength of about 24.4 cm. Calculate the frequency of each of these signals.
4. The door of a microwave oven includes a window made from a metal mesh screen attached to glass. Explain why the metal screen is a critical part of the design.
5. Explain why the specialized light bulbs used for growing plants indoors tend to have a reddish-purple colour.
6. Explain why people who use tanning beds should wear protective goggles.
7. An X-ray technician may deal with dozens of patients requiring X-rays every day. Explain why it is important for the technician to operate the X-ray machine from behind a shielded wall.

Use the following information to answer questions 8 and 9.

Ultrasound is the preferred imaging technology for checking the development of an unborn child. This technology produces images that can be displayed on a computer monitor.

8. Carefully examine the photo of an ultrasound technician scanning the pregnant woman's abdomen with ultrasound. List details from the photo that support the idea that ultrasound is **not** a form of ionizing radiation.
9. Explain why X-rays are not used to monitor the development of unborn children.

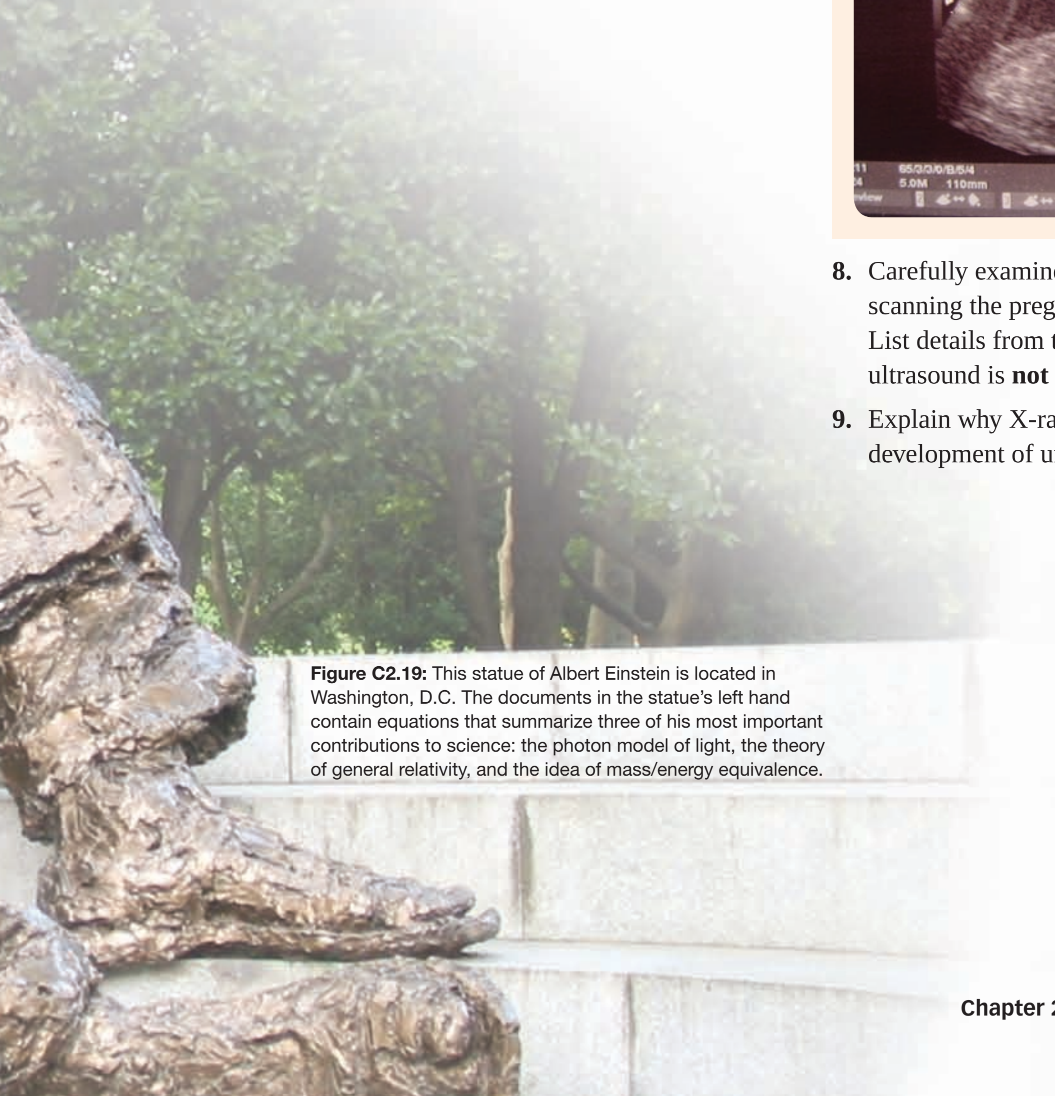


Figure C2.19: This statue of Albert Einstein is located in Washington, D.C. The documents in the statue's left hand contain equations that summarize three of his most important contributions to science: the photon model of light, the theory of general relativity, and the idea of mass/energy equivalence.